

# Laser sounder approach for measuring atmospheric CO<sub>2</sub> from orbit

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**Abstract:** We report on an active remote sensing approach using an erbium fiber amplifier based transmitter for atmospheric CO<sub>2</sub> measurements in an overtone band near 1.57  $\mu\text{m}$  and initial horizontal path measurements to <1% precision.

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## 1. Carbon cycle science approach

Mounting concern regarding the possibility that increasing carbon dioxide concentrations will initiate climate change has stimulated interest in the feasibility of measuring CO<sub>2</sub> mixing ratios from satellites. Currently, the most comprehensive set of atmospheric CO<sub>2</sub> data is from the NOAA CMDL cooperative air sampling network, consisting of more than 40 sites where flasks of air are collected approximately weekly [1]. Although the surface network is extensive, there is a dearth of data in the Southern Hemisphere and most of the stations were intentionally placed in remote areas, far from major sources. Sufficiently precise satellite observations with adequate spatial and temporal resolution would substantially increase our knowledge of the atmospheric CO<sub>2</sub> distribution. Current estimates indicate that a measurement precision of better than 1% will be needed in order to improve estimates of carbon uptake by land and ocean reservoirs [2, 3].

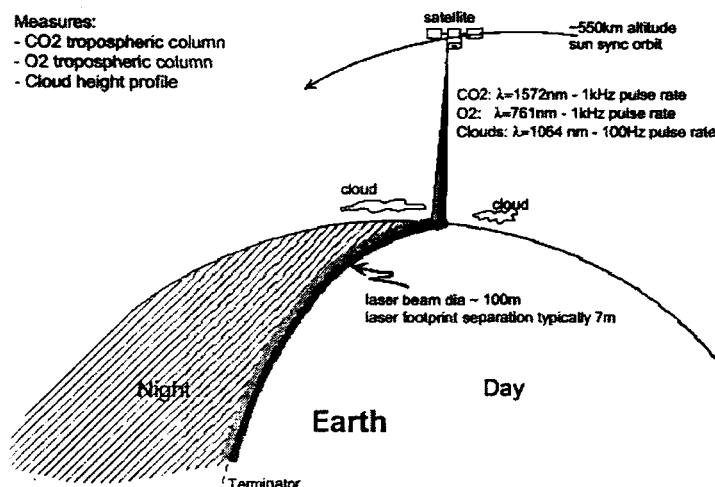


Fig.1. Proposed Laser Sounder Measurement Scenario Concept

Several potential techniques for measuring CO<sub>2</sub> from space are under development. We propose a laser sounder [4] instrument using the differential absorption technique for measuring CO<sub>2</sub> abundance near 1.57  $\mu\text{m}$  and O<sub>2</sub> near 770 nm. The ratio of CO<sub>2</sub> to O<sub>2</sub> will provide a measurement of the dry-air mixing ratio of CO<sub>2</sub>. This quantity should be insensitive to fluctuations in surface pressure resulting from changing topography or weather systems and to fluctuations in humidity. A third channel at 1.064  $\mu\text{m}$  will detect clouds and aerosols in the sample footprint.

Figure 1 shows a schematic view of the measurement scenario concept and the instrument diagram is shown in Figure 2. An important advantage of our active (laser-based) technique over passive approaches is that measurements can be made at any time of day. CO<sub>2</sub> is known to have large diurnal variations near the surface, and biases may result from aliasing of these daily fluctuations. We plan to select a dawn-dusk orbit that would provide measurements near the maximum and minimum daily values.

Vertically resolved CQ profiles are highly desirable, but with available technologies, total column measurements may prove more feasible in the next decade. Our approach measures laser light reflected from Earth's surface and thus provides a column-integrated quantity. However, some profile information may be obtained by observing a spectral line at multiple frequencies of varying optical depth. Pressure broadening provides enhanced sensitivity to lower altitudes in the line wings. This property can be exploited to isolate the variability in the lower atmosphere.

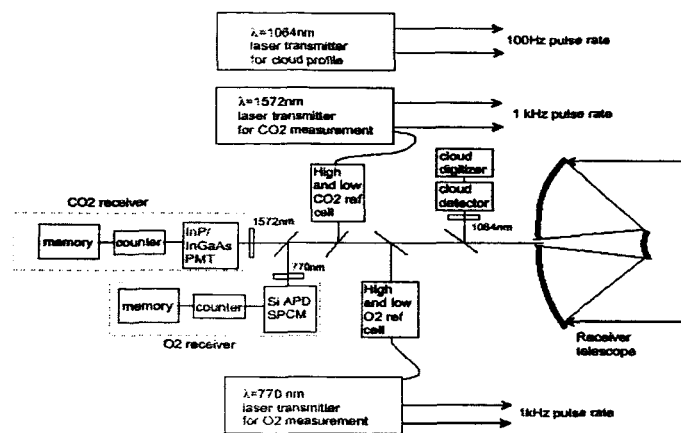


Fig. 2. Proposed Laser Sounder Instrument Diagram

Previous efforts to develop laser-sounder long-path instruments for atmospheric CO<sub>2</sub> measurement include work at the 4.88  $\mu\text{m}$  [5] and 2  $\mu\text{m}$  [6] wavelengths. We selected the spectral region near 1.57  $\mu\text{m}$  based on several criteria. The spectral band consists of discrete narrow lines that are free from interference due to water vapor and other trace atmospheric constituents. The optical depths are strong enough to provide high sensitivity to changes in CO<sub>2</sub> amount, but are not so strong as to be saturated. In addition, this wavelength falls within the telecommunications “L-Band” extending from 1.57 - 1.61  $\mu\text{m}$ . We can therefore leverage a substantial commercial research and development effort focused on improving components in this wavelength region. Single-frequency, narrow linewidth, distributed feedback (DFB) semiconductor lasers are available for the 1.57 $\mu\text{m}$  transmitter. These low power lasers will seed Erbium Doped Fiber Amplifiers (EDFA’s) to generate the high powers needed for operation from orbit. Similar seed lasers will be used with frequency doubling in the transmitter for the O<sub>2</sub> channel at 770 nm. The similarity of the O<sub>2</sub> and CO<sub>2</sub> transmitters is a major advantage of our technique over other active methods, since there are no other convenient sources of laser light at 770 nm that are suitable for space flight.

## 2. Long-path atmospheric CO<sub>2</sub> measurements

We have recently begun making measurements of ambient CO<sub>2</sub> over a long horizontal path [7]. Our experiment is described as follows. A tunable-diode-laser (New Focus Model 6330) wavelength is scanned over a CO<sub>2</sub> absorption line at a rate of 200 Hz with a triangular wave from a signal generator. The laser output is fed through a 40 dB optical isolator to a high-power (5 W) erbium-doped fiber-optic-amplifier (IPG Photonics Model EAD-5) and directed through a custom transmitting telescope (1.5 mradian beam divergence). The light then traverses an open air path (206  $\pm$  4 meter one-way at an average 10 m altitude) to a hard target reflector (0.7 m x 0.7 m flat aluminum plate covered with Moco Model V82 Conspicuity Reflexite Tape) and retro reflected back to the receiver telescope (20 cm Meade). At the receiver, custom optics focus the light on to a 1 mm diameter InGaAs PIN detector (New Focus Model 2034). To improve the sensitivity for longer path measurements, we will replace the PIN detector with a near-infrared photomultiplier tube. The detector/pre-amplifier output is band-limited to 3 kHz and digitized (NI Model PCI-MIO-16E-1 12 bit A/D) at a rate of 100 ksample/s. The resulting transmission plot is shown in Figure 3 (a). Also shown is the theoretical prediction from the HITRAN database (for a 206 m one-way path length and an atmospheric CO<sub>2</sub> concentration of 415 ppm as measured simultaneously by a Licor Model LI-6262 CO<sub>2</sub> Analyzer, see below for more details). The experimental data was scaled to match the calculated transmission, assuming differences were due to a DC offset on the detected signal. A calculated DC offset of 0.25 (transmission units) provides the best fit to the theory.

A simple algorithm to process and retrieve CO<sub>2</sub> concentration in real-time is given by:

$$CO_2 ppm = K \ln \left[ \frac{1}{N} \sum_{i=1}^N \left( \frac{S_{ON}}{S_{OFF}} \right)_i \right] \quad (1)$$

where  $K$  is a calibration constant (determined by making a one-time independent CO<sub>2</sub> measurement),  $S_{ON}/S_{OFF}$  is the measured transmission ratio (ON at 1572.335 nm and OFF at 1572.260 nm), and  $N$  is the number of measurements over the spectral line. Using this differential absorption algorithm, we measured the CO<sub>2</sub> concentration every 10 seconds ( $N=2000$ ). The data were referenced and scaled to match the Li-cor measurement at a single point. Data from the prototype laser sounder and the Li-cor analyzer remained correlated within  $\pm 1$  ppm over 6 hours as shown in Figure 3 (b). With the current setup, nighttime data are of higher quality than daytime observations. This is because we have not yet incorporated a reference path in our prototype instrument to compensate for system changes and the system is most stable during non-work hours.

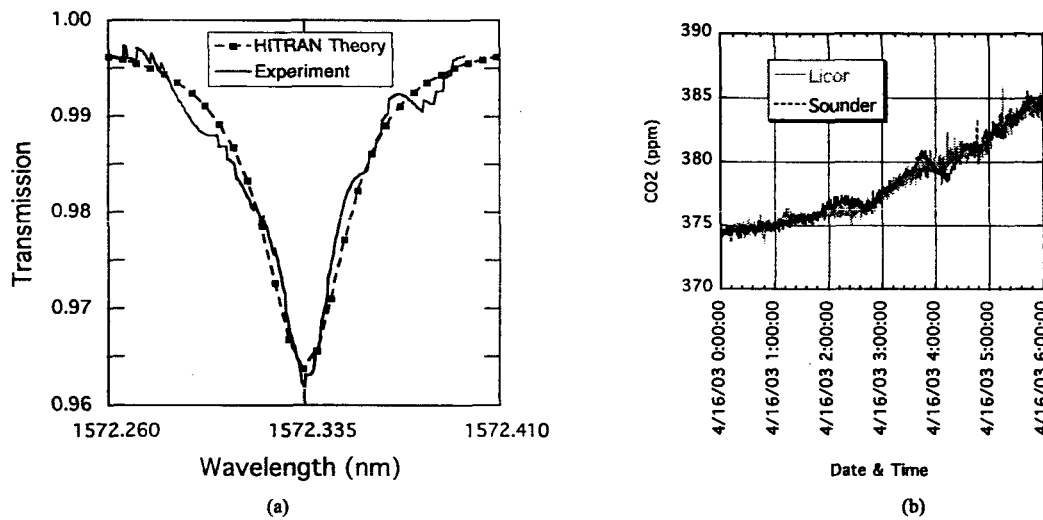


Fig. 3. (a). HITRAN theory and measured ( $N=2000$ ) atmospheric transmission at NASA Goddard Greenbelt, MD for 206 m one-way path on 11/21/02 at 4:50 PM EST (This is a one parameter fit to theory) (b) Li-cor analyzer point measurement and prototype Laser Sounder column measurement (referenced and scaled) comparison.

### 3. References

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